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BOUNDARY-ESCAPE TRACKING: A NEW CONCEPTION OF HAZARDOUS PIO

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ABSTRACT

Pilot-induced oscillations (PIOs) have vexed many designers, scared many more flyers, and killed more than a few pilots and aircraft. In spite of decades of research and hundreds of lessons learned, hazardous PIOs remain a constant threat during most envelope expansion efforts. PIO prediction has assumed that all PIOs are essentially the same thing; a pilot maintaining a condition couples with the aircraft in a way that drives an oscillation. If the pilot's gains are high enough, the entire system is unstable and in severe jeopardy. The purpose of this paper is to challenge this assumption by describing how a previously unrecognized task, 'boundary tracking,' can explain some PIOs—especially the most hazardous sort. This new conception may lead to new methods of predicting, preventing, and recognizing the PIOs that present the greatest hazard to flight test and operational aircrew. Boundary tracking was conceived in an attempt to explain hazardous PIOs, but it may have predictive abilities in many areas of handling qualities design and testing. From minor PIOs such as pitch bobbles to the stop-to-stop PIOs that kill pilots and airplanes, pilots' attempts to *avoid* a condition may explain many events that pilots' attempts to *maintain* a condition cannot.

INTRODUCTION

PIOs have vexed designers and testers since the inception of manned flight. It is telling that the acronym itself cannot seem to find a stable meaning. It started as 'pilot-induced oscillations' but that seemed unfair to pilots so it became 'pilot-in-the-loop oscillations' or 'pilot-involved oscillations.'[1] No matter what the 'I' stands for, PIOs strike fear in the hearts of testers. They drive design decisions and slow development as small oscillations are studied to ensure they can't lead to larger, more dangerous conditions. There are at least a half-dozen criteria for predicting

PIOs.[2] However, these criteria seem to conflict as often as they converge; in spite of decades of research and hundreds of lessons learned, hazardous PIOs remain a threat during most envelope expansion efforts.

Hazardous PIOs are a continuous source of concern, yet short term or controllable PIOs are a routine event in many aircraft. T-38 students and instructor pilots routinely experience small pitch PIOs in close formation. Hang glider pilots often experience roll PIOs during final approach. PIOs are a common occurrence for many pilots initially learning to fly. How can one thing be rightfully feared in so many ways yet routine in so many others? Is a routine hang glider roll PIO really the same kind of thing as the roll PIO that resulted in the loss of a JAS-39 Gripen? Is a routine T-38 pitch bobble really the same sort of thing as the PIO that resulted in the loss of a YF-22?

BICYCLING THE FOOT-WIDE BEAM

A common example given to describe how a task can increase tracking gain is the one-foot-wide beam task. Imagine a rigid beam one foot wide placed between two twenty-story skyscrapers. Now imagine a foot-wide line painted across an unobstructed stretch of concrete. Why is it so much harder to ride a bicycle along the beam than along the line on the ground? After all, even a moderately skilled bicyclist can easily stay within the confines of a foot-wide path. These should be identical tasks—just stay near the center of the beam. Nevertheless, we know that they are not at all identical. We know that one carries a significantly higher risk of going off the edge.

The traditional explanation for the increased difficulty of the elevated task is that the importance of staying on the beam increases the rider's gain so much that the system (that's the bicycle and rider) may be rendered unstable. This explanation assumes that the only task is to keep the bicycle on the path by tracking the center of the path. Though this explanation may provide mathematically pleasing results it misses the actual difference. The suspended beam has two more tasks that the painted path does not: do not touch either boundary. These tasks are part of the human survival tool kit and cannot be ignored—they are literally life-or-death tasks.

With the addition of inviolable boundaries, the tracking task is changed. It is not just a matter of 'gain' or 'workload,' it is the addition of two vitally important additional tracking tasks. Given the consequences of failure, the bicyclist's response to these tasks can be extreme, and might be limited only by strength and reaction time. Tracking the centerline and tracking each boundary are fundamentally different tasks.

Boundaries or limits have long been recognized as a potential PIO 'trigger.' They are thought of as triggering the increases in gain and time in-the-loop necessary to initiate a PIO.[3] While there is no question that approaching a boundary will increase pilot anxiety and effort, the pilot's effort is not focused on the original task, such as staying near the center of the beam. The pilot's effort is focused on the boundary, and the pilot's inputs are based upon the boundary until it is avoided.

TWO TYPES OF TRACKING AND PIO PROPOSED

Point Tracking Point tracking is tracking as it has been traditionally understood. It includes the many pilot tracking models currently used in handling qualities analysis including compensatory control, pursuit control, precognitive control, and the pilot synchronous model.[4] In the case of piloting an aircraft, the pilot controls the aircraft to maintain a desired condition, or 'point,' within a certain arbitrary error band.

Point tracking is how aircraft are typically flown. Whether tracking a pitch attitude, g loading, bank angle, or strafe rag, the pilot controls the aircraft to maintain a desired condition. Perfection is not required and rarely attempted—the pilot will accept error within the limits of the task in order to reduce workload and the tendency to overcontrol. If the aircraft is stable for the task, the pilot may spend a majority of the time 'out of the loop,' reducing workload by allowing small errors and letting the natural aircraft stability do the bulk of the work. While tracking a desired point, the displacement from the condition tends to drive the size of the correction (compensatory control), but the pilot uses a variety of techniques to prevent or minimize overshoots and maintain a stable track.

Boundary Tracking Tracking has traditionally been considered only in the sense of attempting to maintain a certain condition. Sometimes, though, a pilot is called upon to avoid a condition. Any pilot can relate stories of controlling an aircraft only to avoid or escape an obstacle or a limit. Boundary tracking is controlling in relation to a boundary to minimize or prevent an excursion.

Boundary tracking is fundamentally different from point tracking. It is, in many ways, an inversion of the point-tracking task. During point tracking, when the aircraft is approaching a target point, the pilot will reduce control inputs to capture the point. If the aircraft is approaching a boundary, the pilot will increase control displacements as the boundary approaches. Conversely, if the aircraft is moving from a point-tracking target, the pilot will increase control inputs to return to the point. If the aircraft is moving away from a boundary, the pilot will abandon the boundary-tracking task since it is no longer necessary. Boundary tracking is a transient task—it is only used when necessary and is abandoned once the boundary is no longer a factor.

What is a 'Boundary?' The term 'boundary' initially elicits thoughts of physical barriers; these are obviously capable of eliciting boundary tracking. There are a wide variety of potential boundaries:

1. A physical barrier: these barriers might include anything from the ground, to flight lead, to a bird.

2. An aircraft limit: a less obvious though often a no less dangerous boundary. These might include aircraft g limits, roll rate limits, roll angle limits (especially in proximity to the ground), and angle-of-attack limits.

3. The pilot's physiological experience: boundaries related to comfort, such as high side loads or the sort of combined side loads and transient g's that accompany high roll accelerations when the cockpit is not on the roll axis. Transient longitudinal loads may also drive boundary tracking, especially unexpected reductions in cockpit g.

4. Performance standards not directly related to safety: boundaries imposed upon a pilot to measure the pilot's attainment of standards. A student pilot may have boundaries imposed by a syllabus—exceed them might even mean failing the ride. Pilot evaluations often have boundaries on tasks; only a certain amount of error is allowed for a variety of evaluation maneuvers.

5. Combinations of boundaries: a pitch rate boundary will be very different up-and-away than it will be during aerial refueling or landing. A transient unload near the ground will also be much more likely to drive boundary tracking than a transient unload at altitude.

Although boundaries might seem analogous to error bands, they are quite different. An error band represents a region within which the pilot will not attempt a correction. A boundary is the limit of a region within which the pilot is attempting to remain, so the pilot will maneuver as required to prevent exceeding the boundary.

A boundary need not be correctly evaluated or understood by the pilot to result in boundary tracking. From unnecessarily tight tolerances to poorly understood aircraft limits, the boundary that matters to aircraft handling qualities is the boundary that the pilot perceives. Although conservative pilots will tend to place their boundaries within the actual boundaries, the opposite can occur. (If boundary tracking can be hazardous, tracking a boundary outside the true boundary can be deadly!) Identifying the varieties of boundaries and how pilots perceive them will be necessary to apply boundary tracking to the prediction of handling qualities.

Some Thoughts on How Boundary Tracking Happens If we are to understand and apply boundary tracking to handling qualities, we must understand how pilots perceive and track boundaries. This is not a simple problem, yet the rewards may be great.

In order to outline the basics of boundary tracking, the initial conditions of the task must be defined. A pilot, whether actively controlling an aircraft or monitoring an autopilot, is primarily concerned with numerous point-tracking tasks. These often include airspeed, altitude, and heading maintenance but can be much more complex. During a diving weapons delivery, for instance, the pilot may be tracking an airspeed rate and rate-of-change in addition to dive angle and pipper position. Additionally, the pilot is also monitoring the state of the aircraft in relation to the many boundaries that threaten safety or task accomplishment. This monitoring may fall anywhere from unconscious to fully conscious attention, unconsciously monitoring for things like unexpected aircraft motions and consciously monitoring boundaries such as the ground. Even during a relatively simply task, such as maintaining a constant pitch attitude in the heart of the envelope, pilots are monitoring a wide variety of parameters.

Boundary tracking begins when a pilot consciously or unconsciously perceives that a boundary might be exceeded if action is not taken. This perception drives the pilot away from the primary (probably point-tracking) task at hand and into boundary tracking. Boundary tracking is maintained until the perceived risk of exceeding the boundary is eliminated. This feeling of momentary single-mindedness to avoid a boundary is a common experience among pilots.[5]

The Two Major Classes of Boundary Tracking: Avoidance and Escape The implications of a boundary are a critical part of the pilot's response to it. Boundaries always have consequences but these consequences can range from mild frustration to death. Pilots will attempt to avoid the first type of boundary but must escape the second. These classes span a continuum of pilot responses but the continuum is primarily contained within boundary-avoidance tracking, where the pilot's response varies with the perceived need. Boundary-escape tracking is driven by the pilot's survival instinct so it is limited only by the pilot's familiarity with the controls and the pilot's physical strength. Figure 1 illustrates the spectrum of boundary tracking, from simple awareness of an inconsequential boundary to awareness of a boundary as a deadly threat. The transition from the avoidance boundary range to the escape boundary range may be considered the point where the pilot is driven to inceptor movements that would normally be considered excessive.

BOUNDARY TRACKING SPECTRUM

CONSEQUENCE OF EXCURSION:	MINOR TASK DISRUPTION	TASK FAILURE	LOSS OF LIFE OR AIRCRAFT
BOUNDARY TRACKING:	AVOIDANCE	AVOIDANCE	ESCAPE
BOUNDARY-TRACKING PILOT GAIN:	MINIMAL	HIGH (MITIGATED)	MAXIMUM (UNMITIGATED)

Figure 1 Boundary Tracking Spectrum

<u>Boundary-Avoidance Tracking</u> When a boundary does not present a concrete survival threat, a pilot will use 'boundary-avoidance tracking' to prevent or mitigate boundary passage. Boundary-avoidance tracking is commonly used when a point-tracking task has performance limits. For instance, a pilot in close formation may attempt to remain within a given vertical distance of the correct position. The nature of these limits, though, implies that the pilot will not use the maximum control available. While attempting to remain within an avoidance boundary, the pilot may use larger control inputs than desired but will not make the kind of inputs called for by an escape boundary. Pilots are unwilling to make control inputs that will cause discomfort or risk aircraft damage unless absolutely necessary, so boundary-avoidance tracking inputs will be mitigated by the pilot's concerns for comfort and safety.[6]

<u>Boundary-Escape Tracking</u> If the boundary is a survival threat, the pilot will be driven to use every available bit of control to prevent hitting the boundary. The world of aviation is replete with stories of pilots overstressing their aircraft to avoid impact with the ground or another airplane. Pilots that find negative g's uncomfortable will unhesitatingly push the stick full forward to prevent a mid-air collision. This is 'boundary-escape tracking.'

When a pilot, driven by fear, controls to escape a hazardous boundary, there are several likely consequences. First, all inputs will be conservative in the sense that an over-correction is better than broaching the boundary. The input itself will probably be larger than necessary, up to full control input or at least to the limits of the pilot's strength. The pilot will hold the input longer than necessary, and will not release it until escape is obvious or confirmed. Second, the pilot's attention to the boundary will be so complete that it will probably increase the time necessary to return to conscious consideration of other flight parameters. Boundary-escape inputs can create the type of control inputs necessary to save the day because they give little conscious regard to comfort or caution.

Proposed Classes of PIO; 'Point-tracking PIO' And 'Boundary-driven PIO' Pilot involvement in PIOs has long been thought of as existing on a continuum, starting with minor pitch bobbles and continuing through maximum effort stop-to-stop pilot control. Pilot gain defines the position of the pilot on this continuum. Outside the pilot, there is little evidence for a continuum, where everything from rate limiting to display delays are seen as contributing to driving the pilot higher on the gain continuum. The popular view of the pilot PIO continuum can make a minor PIO seem a harbinger of disaster by suggesting the possibility that a hazardous PIO may only require additional gain. Pilot gains will also have different implications for point and boundary tracking. Where a pilot can usually self-limit gain during point tracking and boundary avoidance, a pilot cannot generally self-limit gain during boundary escape. Pilots can track points or boundaries and the PIO implications differ for each.

Point-Tracking PIO Point-tracking PIOs occur while attempting to track a specific point-tracking task. These are the PIOs of traditional analysis.[7]

Boundary-Driven PIO Boundary-driven PIOs are the result of a pilot successively engaging in boundary tracking between opposing boundaries. Boundary-driven PIOs have two major subclasses: 'Boundary-Avoidance PIO' and 'Boundary-Escape PIO.'

- Boundary-Avoidance PIO Boundary-avoidance PIOs are the result of a pilot successively engaging in boundary-avoidance tracking between opposing boundaries. A boundary-avoidance PIO may be indistinguishable from a point-tracking PIO when the boundaries are the limits placed on a particular point-tracking task. As with the point-tracking task, pilot gain is limited by the pilot's comfort. The pilot may reduce or eliminate PIO by dynamically adjusting the boundaries.

- Boundary-Escape PIO Boundary-escape PIOs are the result of a pilot successively engaging in boundary-escape tracking between opposing hazardous boundaries. A boundary-escape PIO is driven by fear and/or survival instinct so control inputs may be limited only by the pilot's strength and available control travel. Boundary-escape events drive the pilot fully into the loop, making it impossible to relinquish control of the aircraft without accepting a boundary excursion or changing the task entirely. If the boundaries are real, boundary-escape PIOs can directly cause loss of the aircraft. Falsely perceived boundaries can still drive boundary-escape PIO but the pilot can recover once it is clear that the oscillations are neither growing nor causing the expected disaster.

Point-Tracking PIO In-Depth During point tracking, pilot gain is driven by a combination of experience, acclimation, desire, error tolerance, and stress. If the pilot gain is driven sufficiently high, a PIO may result. When a PIO is entirely the result of the pilot's attempt to accomplish a point-tracking task, the PIO is a 'point-tracking PIO.'

The severity of a point-tracking PIO is limited by the comfort of the pilot provided the safety of the aircraft is not at stake. Pilots will not intentionally exceed inceptor deflections that create uncomfortable motions or accelerations. Thus, pilots may easily abandon a point-tracking task and end a point-tracking PIO because the task is perceived as optional while the PIO is at least uncomfortable and potentially hazardous.

There are many examples of point-tracking PIOs. The most obvious to many USAF pilots is the classic T-38 pitch PIO in close formation. Most pilots routinely PIO the aircraft in this task and many use the PIO as a sort of warning that they are becoming too aggressive. Bobbles, or momentary PIOs, are another good example and are routinely seen during pitch capture tasks when the aircraft is prone to overshoot. Short-term PIOs, excited by high pilot gain and easily exited without hazard, seem to be a routine part of flying many aircraft. Pilots may use these PIOs as feedback to indicate they've exceeded the maximum useful gain for the task.[8]

Boundary-Driven PIO In-Depth In most cases boundary tracking, whether to avoid or escape a boundary, is an unavoidable pilot response. Boundary-avoidance tracking calls for mitigated inputs and can help a pilot maintain desired parameters. Boundary-escape tracking can drive the unmitigated inputs necessary to prevent death and destruction by ignoring the risks of distress and damage. However, boundary tracking may leave the pilot set up to assault an opposite boundary. Boundary-escape tracking is especially prone to this because of the way it drives pilot inputs to the extreme in both magnitude and time. If a pilot exits from one boundary-tracking event to find another boundary rapidly approaching, the succession of boundary-tracking maneuvers may create a sustained PIO. Recall the example of the foot-wide beam; a survival-driven response at one side may result in an unrecoverable vector toward the other side. A succession of boundary-escape events is especially hazardous and may explain many of the worst PIO events.

Several elements are necessary for a boundary-driven PIO to occur. First, and most obvious, is the presence of opposing boundaries. All that matters with the opposing boundaries is that the maneuver used to recover from one be the input necessary to drive the aircraft toward the other. For instance, a descent rate near the ground might drive an aft-stick boundary-avoidance response that would subsequently assault an angle-of-attack boundary. Second, the boundaries must be near enough that recovery from one becomes an assault on the second. Third, for the PIO to be unstable, it seems likely that the system frequency must fall in a range dependent upon the pilot, aircraft, and task. A boundary-driven PIO might last just one cycle or it might grow out of control.

Pilots are warned to 'get out of the loop' or 'freeze the stick' to stop a PIO, yet highly experienced pilots occasionally find this impossible. Indeed, this well-meaning advice may be useless for the worst PIOs. During a boundary-escape PIO, the pilot may be continuously in the loop at extremely high gains. The continuous threat of one boundary or its complement keeps the pilot in the loop. Thus the most severe PIOs—boundary-escape PIOs—continue even if the pilot knows that releasing or neutralizing the controls is the best way to stop a PIO. Boundary-avoidance and point-tracking PIOs, on the other hand, are easily exited once the pilot recognizes the PIO—the PIO is a greater risk than the task that started the oscillation, so exiting the control loop is relatively easy. Boundary-escape PIOs present a very different problem and require a different approach for recovery.

It seems likely that an unstable point-tracking or boundary-avoidance PIO can progress into a boundary-escape PIO given the right conditions. If the less hazardous PIO drives the pilot into opposing hazardous boundaries, a boundary-escape PIO may ensue before the pilot can quit the first, less hazardous PIO.

Boundary-driven PIO, whether caused by boundary avoidance or boundary escape, is an additional source of PIO that has not been considered in the past. It seems that there is little doubt that boundaries can cause the necessary pilot gain and involvement to produce PIO in an otherwise stable aircraft. Perhaps a deeper understanding of boundaries and how pilots notice and track them can aid in the prediction and prevention of many PIOs, especially the most hazardous boundary-escape PIOs.

<u>Examples Supporting Boundary-Driven PIO</u> Aviation lore is replete with examples of PIO but PIO is not limited to aircraft. Both boundary-driven PIO and point-tracking PIO are not uncommon whenever a human is closely controlling something. The following examples of boundary-driven PIO, mostly taken from the author's experience, will illustrate boundary-driven PIO by looking at the event and the mental process that drove the oscillation.

The first example causes many solo automobile accidents, especially on long and boring drives. Imagine a driver that has fallen asleep on the highway. When the vehicle's wheels leave the road the driver wakes to find the car in a hazardous situation. Many drivers, when waking to this situation, immediately enter boundary-escape tracking. Fear of leaving the road or going further off the road results in a large control movement to return to the road. (Note the important distinction between making that control input to correct back to the center of the lane.) The driver maintains this control input until the vehicle is clearly headed back onto the pavement. Unfortunately, the size of the initial fear-driven input often results in a severe overcorrection that the driver does not recognize as such until the initial boundary-escape task is complete. Thus, the driver inadvertently places himself into another boundary-escape maneuver—this time avoiding the other side of the road. The second boundary-escape maneuver is often sufficient to cause a rollover or loss of control. Many driver education courses emphasize that once you leave the road unintentionally, you should stay there while slowing for a smooth reentry. Unfortunately this advice, like the admonition "don't look down," may not be of much use to a driver awakened by wheels rattling on dirt and rocks.

The author experienced a PIO during pilot training that can be described as a boundary-avoidance PIO that rapidly progressed to a boundary-escape PIO. Flying solo on the wing for a formation approach in the T-38, the author entered a point-tracking pitch PIO while transitioning to the 'stack level' position. The PIO began at about 500' AGL so it only took about one cycle for the hazardous boundaries to show themselves. The author immediately transitioned to a boundary-escape PIO, oscillating between the hazards of losing sight of lead and hitting the ground. Fortunately, the former hazard was the first 'hit,' and losing sight of lead gave the author the opportunity to get out of the loop and change the task to building lateral spacing.

The author observed a stop-to-stop yaw PIO during a USAF Test Pilot School handling qualities flight test techniques (FTT) training sortie. This PIO was particularly important because the circumstances served as a catalyst to form the concept of boundary-escape PIO in the author's mind. The sortie was a curriculum ride in a T-38 with a talented pilot. Normally, several simulated strafing runs are accomplished late in this sortie to examine high-gain fixed-gunsight tracking but the student was clearly not being challenged by the task. The author modified the task to a rudder-only yaw-tracking task accomplished first with the yaw damper on and then with it off. As expected, the student found the aircraft handling qualities for the damper-on yaw tracking task to be very good. When the maneuver was repeated with the yaw damper off, the result was entirely different. The author observed a few yaw oscillations then the student said something unintelligible and recovered about 3,000 feet early with 5.5 g's instead of the normal 4 g's. The student then asked in a very concerned tone of voice if the aircraft was directionally stable. After reassurances that the T-38 is directionally stable throughout its flight envelope, the flight was continued. The specifics of the student's experience became clear during debrief. As he began the second high-gain tracking task by attempting to capture a target with a directional input, the aircraft overshot significantly. The size of the overshoot was magnified by the fixed gunsight and his previous experience with the yaw damper on. He attempted to return the pipper to the target but it overshot again—even more this time. The size of the second overshoot was large enough that he became concerned that the aircraft might pass a yaw limit and depart so his next input was intended to prevent this large overshoot. The nose came back further still and he made yet another, even larger, input to prevent yaw departure. This continued for a few more overshoots until he became convinced that the aircraft was unstable. Since it seemed impossible to prevent a yaw departure, he elected to discontinue his attempts to stabilize the aircraft so he could reduce his dive angle and airspeed in preparation for what seemed to be a possible ejection. The residual dutch roll oscillations quickly damped out during the recovery. It took a while to convince the student that the divergent oscillation was the result of a PIO. While it is well known that a pilot, attempting to stabilize a lightly damped system, can cause a PIO, this student's description of his experience made it a clear case of a point-tracking PIO rapidly developing into a boundary-escape PIO. Although his boundary-escape efforts might be described as an attempt to stabilize the system, his timing was based entirely on preventing the magnitude of the yaw oscillations from exceeding a perceived limit.

<u>Section Conclusion</u> Many PIOs are the result of a pilot attempting to maintain a condition. These point-tracking PIOs are how PIOs are traditionally understood. However, a pilot alternately avoiding or escaping opposing boundaries may also cause a PIO. These boundary-avoidance and boundary-escape PIOs are made evident by the pilot's description of the PIO. Many hazardous PIOs may be the direct result of boundary-escape tracking.

MODELING BOUNDARY-DRIVEN PIO

In the closed-loop system of pilot and aircraft, boundary awareness might affect the pilot's feedback into the system in predictable ways. Researchers have created a variety of pilot models to explain or predict pilot tracking behavior. These models are based on point tracking; they operate on an error signal generated by comparing the desired state with the actual state. Boundary tracking must be modeled by feeding back a signal based upon the boundary, such that the gain applied to avoid the boundary increases as the boundary is approached. A simple model was designed to investigate boundary tracking using The Mathworks, Inc. Simulink® software. This model, though extremely simple in comparison to the human mind, produced results strongly supporting boundary tracking as a source of PIO.

The simplest model of human tracking, consisting of feeding back pure gain with a time delay, was used to simulate point tracking. Boundary tracking feedback was added for each boundary. A limit on feedback from both the point-tracking and boundary-tracking feedback loops was used to simulate the pilot's self-imposed 'comfort limits' and the feedback limits that would be imposed by an actual control system.

Preliminary Assumptions for the Model A simplified model requires simplifying assumptions that do not trivialize the result. The following assumptions limited the model to one subset of boundary tracking.

1. *Time to the boundary is the critical parameter.* The feedback loop computing boundary-avoidance gain for each boundary computed the threat of the boundary based upon the instantaneous displacement and rate of approach to the boundary. The amount of the boundary-tracking feedback was assumed to vary linearly between some maximum time to the boundary (no feedback) and a minimum time to the boundary (maximum feedback).

2. *If the system displacement is outside of a boundary, the maximum returning gain is held until the system is once again inside the boundary.* Obviously this assumes that the boundary may be exceeded (such as a g limit).[9]

3. *At any given moment, attention of the tracker is focused entirely on either a boundary- or point-tracking task.* A point tracker consisting of simple rate feedback with adjustable time delay and gain was included to model point tracking. The model continuously computed time-delayed point-tracking feedback and boundary-tracking feedback and the feedback with the greatest magnitude at any given moment in time was exclusively applied.

4. *There is no time delay to transfer from one type of tracking to the other.* Although this seems to be an oversimplification of what seems an obvious result of changing mental states, it is a conservative simplification for the purposes of this model. Any additional time delay as the tracker switches from one type of tracking to another can only serve to further destabilize the system.

5. *Both boundary tracking and point tracking have a 'gain' and a 'maximum feedback.'* Modeling boundary avoidance requires numerous non-linear elements. Since the aircraft limits the pilot's ability to make inputs by limiting inceptor rates and displacements, the model was designed to allow varying both the gain and the maximum feedback. This allowed analyzing the results of smaller limits maintained by the pilot during point tracking as opposed to higher limits (such as control travel limits imposed on the pilot) during boundary-escape tracking.

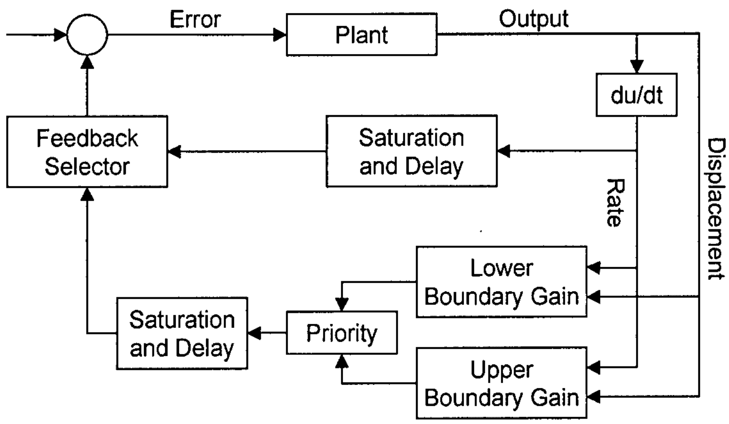

Figure 2 Simplified Block Diagram of Model

Model Construction The basic system, or 'plant,' was kept as simple as possible. A spring-mass-damper system was employed for this. By varying the constants of the plant, the effect of differing baseline stabilities could be investigated. Point-tracking gain (rate feedback) was adjustable and passed through an adjustable saturation filter to limit the applied gain. The boundary-tracking gain was adjustable as well. All values were entirely notional; they were not based on a particular aircraft or system aside from the spring-mass-damper plant. The important results are illustrated by how the behavior of the system changes as given parameters are changed so the results are shown without scales.

Simple Boundary Tracking as the Boundaries are Changed The first question that must be answered is 'What happens as the boundaries move in with all else held equal?' To answer this question, the plant was adjusted to have moderate damping and a small singlet was used to drive the system into oscillation. Figure 3 shows just such a system with the boundaries well outside 'awareness.' The upper line, labeled "Boundary Tracking Feedback" is the applied boundary-tracking feedback from both boundaries subject to the assumptions. The lower curve is simply the system displacement (as labeled). The driving singlet was left out for clarity. With no tracking, the system displays moderate damping after the initial perturbation.

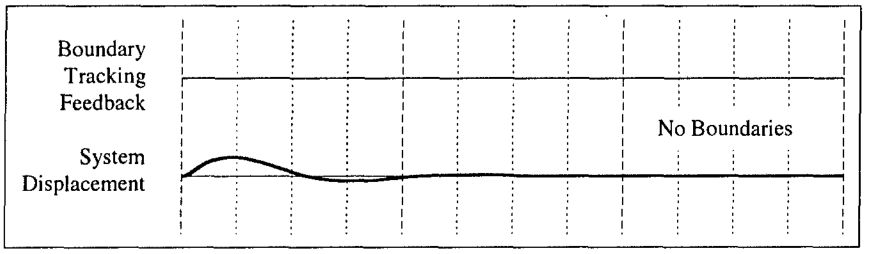

Figure 3 A Damped System with No Boundary Tracking

When the boundaries are placed at a distance such that the displacement and rate of the initial movement cause boundary awareness, a short boundary-avoidance input is made, illustrated by Figure 4. (The lines equidistant from the system displacement center point are the boundaries.) Note that the input is less than the maximum input allowed and that it does not affect the long-term response except by shortening the time of the initial excursion. With no point tracking and with boundary tracking no longer excited, the system returns to its open loop response after the short boundary-tracking input.

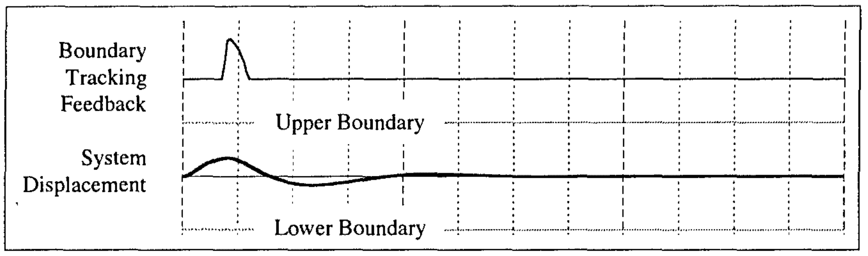

Figure 4 A Single Instance of Boundary Tracking

Further reducing the distance to the boundaries results in an increased number of boundary-tracking events. Figure 5 illustrates this situation with two boundary-tracking events. (Note that the position of the boundaries used in Figure 4 are designated with dotted lines.) It is immediately obvious that the frequency of the system has increased with the boundary tracking—this is typical of feedback systems whether point or boundary feedback is applied. The addition of the second boundary response has an appearance similar to a 'bobble' PIO.

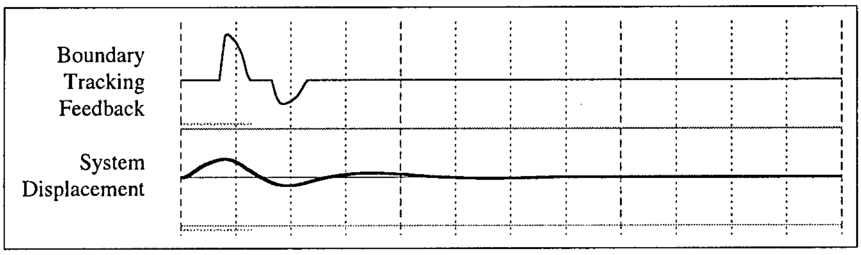

Figure 5 Two Instances of Boundary Tracking

A small additional reduction in the boundary displacement drives the system into a boundary-driven oscillation. In the example pictured in Figure 6, the system boundaries and awareness parameters are such that the oscillation stabilizes within the boundaries. There has been no change in the basic spring-mass-damper system and no point-tracking feedback is being applied.

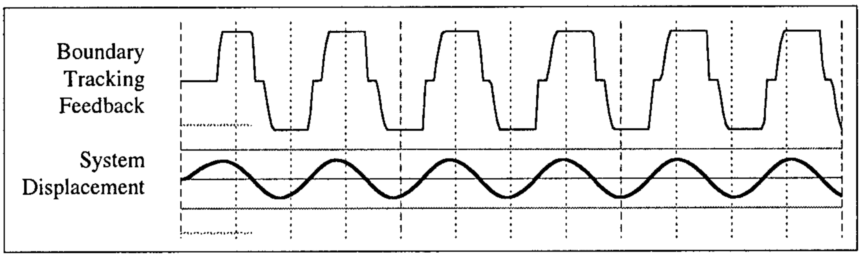

Figure 6 Onset of Boundary-Driven Oscillation Within the Boundaries

As the boundary displacements are reduced further, there is very little change in the system until the displacement of the oscillation exceeds either boundary. As long as the oscillation remains inside the boundaries, the frequency and amplitude varies very little as the boundaries are moved closer to the center. Figure 7 illustrates the result if the oscillation exceeds a boundary—a rapid increase in amplitude to a new and typically much larger displacement. The frequency also decreases significantly as the displacement exceeds the boundaries until the oscillations reach their new stable state.

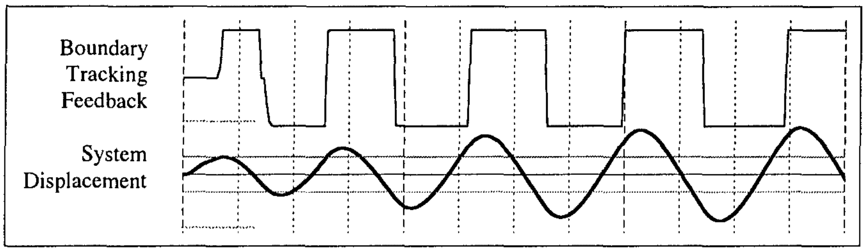

Figure 7 System Oscillations Exceed the Boundary

The cause of the increase in displacement of the oscillations is important. If, as assumed in the creation of the model, the maximum boundary-tracking gain is held whenever the system is displaced outside a boundary, the returning velocity continues to increase until the system returns within the boundary. At this point, the opposite boundary has already become a threat and the maximum opposite gain is applied. This is an unstable situation and the size of the excursions will continue to increase (along with the period of the oscillations) until a stable oscillation is reached, constrained by the feedback limits.

<u>Progression from Unstable Point-Tracking Oscillation to Boundary-Escape Oscillation</u> Small amplitude point-tracking PIOs are a common occurrence in many aircraft and flight conditions. Most of these PIOs start very small and may not be recognized until the amplitude becomes uncomfortable. A trained pilot can easily recognize the increasing amplitude and 'back out of the loop' before the PIO becomes uncomfortable or dangerous. These PIOs also tend to have limited amplitude because the pilot will not exceed control movements known to produce uncomfortable forces.

In the previous example, boundary-driven inputs and oscillations were started by a system with an initial perturbation that assaulted a boundary. The following examples use the point tracker to create an unstable point-tracking oscillation (with the amplitude constrained by a gain limit) and the boundaries are moved closer with each trial. In this system, the limit of the point-tracking feedback is half that of the boundary-tracking feedback to simulate the larger control inputs driven by boundary-escape tracking.

Figure 8 shows the system with no boundary tracking. (Point-tracking feedback and total boundary-tracking feedback are given in the top two curves. 'Applied Feedback' is the actual feedback applied to the systems based on the assumptions. The lighter lines on either side of the system displacement are the boundaries.) Note how the initial very small displacement steadily grows until the feedback limiter stops the divergence. This is analogous to a pilot limiting inputs for the sake of comfort. In an actual PIO, of course, the pilot would momentarily abandon this point-tracking task to stop the PIO.

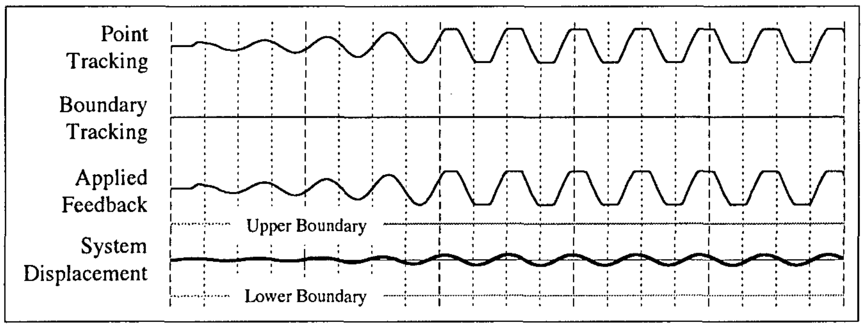

Figure 8 Limited Unstable Point-tracking Oscillation Without Boundary Tracking

With the boundaries a little tighter, the first instances of boundary awareness occur. Figure 9 illustrates this awareness when the resulting boundary-tracking feedback is insufficient to change the total feedback. The gain driven by the boundary-tracking task is less than that driven by point tracking so the applied tracking is unchanged and the behavior of the system remains as if there were no boundary tracking at all.

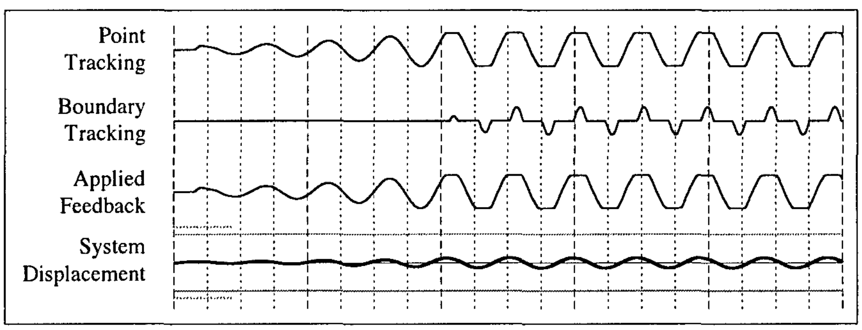

Figure 9 Boundary 'Awareness' Without Boundary Tracking

With tighter boundaries, boundary tracking eventually becomes predominant and rapidly drives the system to larger oscillations. The system goes from mildly unstable in point tracking to highly unstable in boundary-escape tracking. Nevertheless, the final oscillations remain inside the boundary because the control limit is reached. There have been instances of stop-to-stop PIO that never exceeded aircraft limits—this is analogous. Figure 10 illustrates this progression.

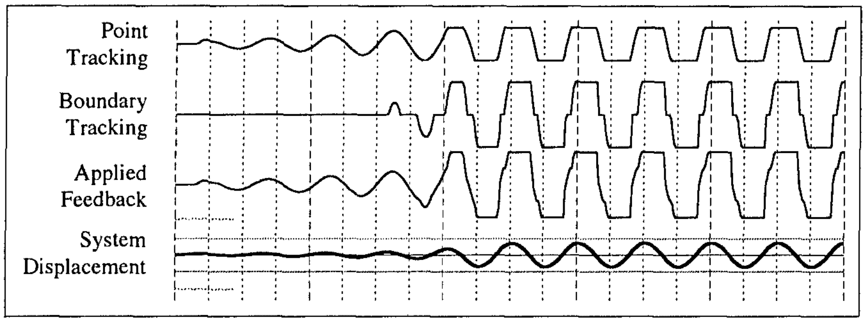

Figure 10 Boundary-Escape Tracking Drives System Unstable until Stopped by Control Limits

As in the case with pure boundary-driven oscillation, if the boundaries are close enough, the oscillations will exceed the boundary. Figure 11 illustrates two separate cases of this for the given system. As soon as the increased control movements driven by boundary-escape tracking are brought to bear, the system is rapidly driven beyond the very boundaries that drove those control movements. The worst case, shown on the right side of the figure, illustrates how a very small, perhaps even unrecognized, point-tracking oscillation can rapidly become a stop-to-stop boundary-escape PIO. Note that the first significant boundary-escape input is all that is required to take the system outside of the upper boundary.

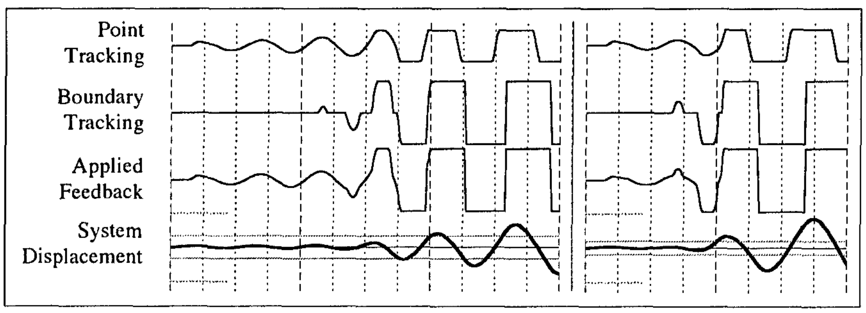

Figure 11 Smaller Boundaries Driving the System Catastrophically Unstable

One of the most important aspects of boundary avoidance is the idea that boundary-escape tracking can drive the system to its maximum gains and maximum control inputs. Whether the system is driven into boundary-escape tracking by an outside disturbance or by unstable point tracking, once boundary-escape tracking is engaged the resulting instability can be extreme.

Modeling Conclusions These examples plus many hours spent by the author examining the effects of varying parameters strongly support the following conclusions:

1. Unstable boundary-escape oscillations tended to grow 'explosively' until reaching the boundary tracker gain limits.

2. Feedback inputs for a boundary-escape oscillation that has diverged to the gain limits are characterized by stop-to-stop inputs.

3. Boundary-escape tracking produces extremely nonlinear ('cliff-like') results. Very tiny variations in gain, time delay, or boundary awareness parameters in the boundary-tracking feedback loop marked the transition from a moderately damped boundary-escape response to rapidly divergent oscillations.

4. Increased feedback delay was an especially powerful driver of boundary-escape oscillations.

5. Unstable point-tracking oscillations can rapidly transition to catastrophic boundary-avoidance oscillations once boundary awareness is achieved. The transition may be marked by an explosive increase in feedback (inceptor) inputs.

6. Boundary-escape PIO can occur where point-tracking PIO is not present. If the boundaries are sufficiently tight and/or the increase in gain brought by boundary-escape tracking is sufficiently greater than the normal gain for the point-tracking task, a boundary-escape PIO can quickly arise from a disturbance large enough to assault one of the boundaries.

IMPLICATIONS FOR PIO PREDICTION AND PREVENTION

The evidence is clear: from the results of modeling to the feedback from numerous test pilots, boundaries have driven and will continue to drive adverse pilot-aircraft coupling. Where does the aircraft development community take this idea? What paths are likely to be productive? What can the community do now? The following questions must be addressed if boundary tracking and its many implications are to serve the community of aircraft designers and testers.

Can We Learn How Humans Perceive Boundaries and What It Takes to Provoke a Boundary-Tracking Response? It seems highly unlikely that pure research efforts into the human mind have not investigated many elements of boundary tracking. A quick survey of the state-of-the-art in cognitive science, psychology, and physiology revealed that numerous studies have been completed in an attempt to quantify animal (and human) reactions to a variety of stimuli including visual and somatosensory inputs. Cognitive scientists are using scanning techniques to map the brain and working steadily toward an understanding of consciousness and volition. The 'fight/flight' response is widely cited and the implications seem well understood. Any research effort into the specifics of boundary tracking must start with a survey of what is known.

As discussed earlier in this paper, there are probably many possible causes for boundary tracking. Some of these will be instinctive and others a result of training. Some will be obvious and others subtle. Test pilots that have experienced boundary-driven PIO (especially boundary-escape PIO) will be a rich source of material for investigation. Their stories and the data from their flights may contain significant answers or point to productive research paths.

Instinctive responses probably cause some boundary-escape events. Humans share instinctive responses with many animals, so past animal testing of instinctive survival responses might be a fruitful path for additional research.

Direct research may be difficult for boundary-escape tracking because of the practical and ethical difficulties involved in provoking a fear- or survival-driven response. The author has had the opportunity to attempt to play-act boundary-escape PIO in several different airframes. Play-acting can produce boundary-escape tracking and PIO but, since the impact of fear is simulated without the actual fear, the trigger for the boundary-escape maneuver or PIO must be, for now, an educated guess. Properly conducted boundary-escape testing can result in rapid full control deflections so the vehicle and conditions chosen must be capable of handling these types of control inputs. Variable stability aircraft, complete with safety trips to prevent aircraft damage, seem uniquely suited to this type of testing.

Ground-based simulators may not be viable for studying boundary-escape tracking. Indeed, the very qualities that make simulators such effective design tools may make them entirely unsuitable for testing actual fear-based responses such as boundary-escape tracking. By eliminating the risks involved in actual flight, they eliminate the fear-based responses that are the foundation of so many boundary-escape events. On the other hand, pilots in simulators may be able to intentionally duplicate fear-based responses. Testing by duplicating normally inappropriate pilot actions is analogous to stall and departure testing, especially when investigating the result of departure-inducing or recovery-inhibiting flight control inputs. It may be possible to train test pilots to use the simulator in this manner.

Identification of a boundary is not enough. The way humans respond to a boundary—the way risk is assessed through instinct or habituation—is a critical part of the knowledge necessary to use the data in boundary-driven response prediction. For instance, the runway is an obvious boundary during landing, but its treatment as a boundary is not. Is it a combination of height, descent rate, controllability, and structural strength? Is it a combination of pitch, pitch rate, and the above? How are these factors weighted? Are there instinctive fixed triggers at play? A complex question, to be sure, but the answers may provide significant dividends.

Research into specific instances of boundary tracking is necessary to enable prediction of boundary-driven tracking and PIO. Although a thorough survey of the relevant literature may produce some results, much research will remain. The goal of this research might be to catalogue the types of situations that drive pilots into boundary-avoidance or boundary-escape tracking.

<u>Can We Predict Where Boundary-Tracking PIO Might be a Hazard?</u> If a catalogue of boundary-escape tracking responses can be created, it could be used to examine flight envelopes for possible boundary-escape triggers during the design phase. The catalogue may also allow generalization to simplify boundary-escape prediction. Regardless, understanding how pilots perceive and respond to boundaries will aid designers by providing a list of situations to design out of the system if possible. For instance, should pilots have an instinctive response to a threshold cockpit g unload in proximity to the ground, the aircraft response might be adjusted to prevent exceeding this threshold. In the case of necessary boundary-escape maneuvers, the resulting control inputs and response can be examined for the existence of an opposite boundary that might cause boundary-escape PIO.

<u>Can Awareness of this Phenomenon Aid PIO Prevention?</u> The task of riding the foot-wide beam illustrates the concept of boundary-escape PIO but it also begs the question: How does a circus performer successfully complete similar tasks? Safety devices obviously help but they have to be designed to work only when necessary so they do not limit mission accomplishment. Increased theoretical understanding of boundary tracking will probably make solutions apparent but, until then, pilot awareness of the phenomenon can help.

Boundary-Escape PIO Prevention in Flight Test In the short term, awareness of boundary tracking and boundary-escape PIO may provide a significant benefit. The author has personally experienced boundary-avoidance and boundary-escape tracking since developing the theory. Awareness of these types of tracking allows for rapid categorization and tends to channel attention in helpful ways. For instance, a test pilot that understands the dangers of boundary-escape tracking and has the ability to immediately recognize it may treat the threatening boundary-escape PIO as a greater survival threat than one of the boundaries. This new understanding and prioritization of threats may encourage the pilot to choose a lower risk exit to the maneuver or choose the least dangerous boundary to exceed. Perhaps test pilots with an understanding of boundary-escape tracking may be able to recognize the transition to boundary-escape tracking in time to limit the consequences. A test pilot that is alert to the indications of boundary-escape tracking may be able to recognize an impending PIO before the survival instinct makes relinquishing control impossible.

Boundary-Escape PIO Prevention in the Operational Environment The aircraft design and test community must strive to produce aircraft that pilots can use with minimal risk of encountering boundary-escape PIO. History shows that in spite of their best efforts, it is likely that the potential for these events will remain hidden somewhere in the task envelope. The typical operational pilot's poor understanding of PIO indicates that boundary-driven PIO will not be well understood either. On the other hand, just as many pilots can recognize a PIO when it occurs and can learn to avoid and exit relatively stable PIOs, perhaps operational pilots can be given a mental picture of a boundary-escape PIO and some recovery techniques. But this is a poor backup to building aircraft that actively or passively prevent boundary-escape PIO, and makes the work of the design and test team all the more important.

What are the Implications for Flight Test Techniques (FTTs)? Current FTTs are designed to find point-tracking PIOs. These FTTs include high-gain tracking tasks such as handling qualities stress testing and high-gain zero-error tracking. Due in part to the necessity that they be accomplished in conditions where a PIO cannot cause loss of the aircraft (generally at altitude and with plenty of spacing from other aircraft), these FTTs cannot elicit true boundary-escape tracking.

Cooper-Harper tracking tasks remain a valuable part of handling qualities testing. They provide useful results in relation to realistic criteria for mission accomplishment. Sometimes aircraft PIO affects the ability of the pilot to conduct the task (even if the result is still characterized as Level I). These PIOs can be the result of point-tracking or boundary-avoidance tracking—after all, the desired and adequate criteria given for any Cooper-Harper task are ready-made boundaries. It may not be possible, or even necessary, to eliminate these PIOs as long as the desired criteria will not drive the majority of operational pilots into PIO. PIO may remain if pilots attempt tighter tracking than necessary, but these point-tracking or boundary-avoidance PIOs need not be considered hazardous provided they are very unlikely to drive the pilot into boundary-escape tracking.

Testing for boundary-escape PIO is another problem altogether. If a boundary-escape PIO is predicted, how do you safely test for it? If it is not predicted, how do you demonstrate that it is not a threat? Methods for identifying point-tracking and boundary-avoidance PIOs will probably not identify boundary-escape PIOs, except in extreme or obvious circumstances. How do we test for a response that requires the pilot to 'lose control' between two boundary-escape tracking tasks? Current FTTs are not sufficient but provide a starting point.

Flight test as a discipline has powerful techniques for testing high-risk events. From stall, departure, and spin testing to flutter testing, the flight test community has created build-up processes and safety systems to allow a relatively safe progression into hazardous events. A similar approach is required for boundary-escape PIO. Build-up might include test pilots duplicating boundary-escape tracking using flight test displays presenting known boundary-escape parameters. These tests could be flown at altitude and with safety systems that monitor aircraft parameters and automatically trip to a stable state should pre-determined parameters be exceeded.

In any case, test pilots must be able to immediately identify when they inadvertently engage in boundary-escape tracking. Proper training may prevent a hazardous boundary-escape PIO before it can start, while alerting the test team of the potential for such PIOs to occur.

REVISITING THE FOOD-WIDE BEAM

Boundary-escape tracking and the resulting PIO make the high-altitude bicycling task nearly impossible for most bicyclists. Even though the point-tracking task of staying near the center of the beam would be affected by higher gains between the skyscrapers, a rider might have a chance with just those higher gains. But if the bicycle approaches the edge in a way that threatens a fall, the rider will momentarily abandon the task of remaining near the center and take up the task of avoiding the precipice. Overcorrection is likely and, within an oscillation or two, successive overcorrections will result in a fall.

The only hope for the rider is the proficiency to stay near the center of the beam and the practiced ability to mitigate boundary-escape tracking should the edge threaten. Once the rider *knows* that boundary-escape tracking may be as dangerous as the boundaries themselves, the task begins to become possible.

CONCLUSION

Aircraft handling qualities have traditionally been viewed in terms of the pilot attempting to maintain a desired state through point tracking. This assumption simplified analysis and allowed for many advances in understanding how pilots fly airplanes and how to make airplanes safe and effective. However, pilots occasionally engage in another type of tracking that breaks down the point-tracking assumption. Surrounded by boundaries both hazardous and harmless, pilots occasionally abandon the original task to ensure these boundaries are not exceeded. When driven by fear into boundary-escape tracking, their gains and control inputs become limited only by their strength and the control stops. Although point tracking can produce PIOs, it may be that pilots engaged in successive instances of boundary-escape tracking produce the most hazardous PIOs. Regardless, test pilots must be aware of the implications when they transition to boundary-escape tracking. With this awareness, perhaps they will be better prepared to find a way out of an encounter with boundary-escape PIO.

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[1] National Research Council, p. 1.

[2] Mitchell and Hoh, p. 61.

[3] McRuer, Figure 30, p. 78.

[4] National Research Council, pp. 123-125.

[5] The author has discussed the idea of boundary avoidance with numerous pilots. The concept resonates strongly and each pilot immediately recalled actual instances of boundary tracking (often boundary-escape tracking and several pilots immediately offered personal examples of boundary-escape PIO).

[6] It should be noted that Cooper-Harper tracking tasks, by using desired and adequate performance limits, come with built-in boundaries that may not exist for the operational pilot. The addition of these boundary-tracking tasks may affect the outcome of the evaluation and reduce the accuracy of the flight test evaluation, especially if the Cooper-Harper "desired" and "adequate" criteria are not a concern to the operational pilot.

[7] McRuer, Figure 2, p. 15.

[8] Pilot use of PIO as an indicator of excessive gain (analogously to stall warning as an indicator of maximum instantaneous performance) is the subject of ongoing research at the USAF Test Pilot School.

[9] The primary effect of this characteristic is to increase the effective phase lag of the boundary-tracking feedback when the magnitude exceeds the boundary. Any delay in removing the boundary-tracking feedback after the magnitude stops increasing outside the boundary will produce the same effect, but to a lesser degree.

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